Campaign: Exploring the quantum world with a third generation Ultra-cold atom facility

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Cold atom experiments belong in space. Advantages of microgravity include longer free-fall observation times and the ability to confine and manipulate delicate atomic samples with remarkably small forces, which has led to extraordinarily cold temperatures. Mixtures of different atomic species overlap perfectly, as they do not feel different tugs from gravity, and there are no density gradients across samples. In addition to microgravity, instruments may be able to utilize the vast range of novel reference frames and distance scales accessible in space, the incredibly low vacuum of interplanetary space, or even the cold temperatures of the cosmic background which may allow for the use of passively cooled superconducting magnets or the elimination of perturbations from blackbody temperatures.

The Cold Atom Lab (CAL) was launched in May of 2018. Since that time it has covered a distance of more than 5 A.U. around the Earth and performed over 100,000 individual cold atom measurements. It is operated remotely from the Jet Propulsion Lab, and since March 2020 from the team's home offices and living rooms. Accomplishments have included detailed observations of Bose condensation in microgravity[1], observations of Delta-kick cooling [2] and "extreme adiabatic cooling"[3] and observations of cold atoms in spherical shell ("bubble") geometries. [4] Atom interferometry has also been observed, and explored in several configurations and applied to a few simple measurements. [5] Cold atom experiments involving mixtures of rubidium and potassium have also begun. A key technical achievement is the demonstration of the ability of astronauts to repair and upgrade complex cold atom systems.

CAL, along with a previous sounding rocket experiment, MAIUS,[7] can be considered the "first generation" of cold atom instruments, where, in addition to performing unique science that can only be carried out in microgravity, one of the primary goals has been to gain understanding and experience of how to manipulate atoms in microgravity and demonstrate a myriad of tools that will be used in future missions. Emphasis was on compact, ruggedized designs rather than achieving performance comparable to state of the art (SOA) facilities on Earth. A joint DLR-NASA project ,BECCAL, [8] along with a future upgrade to CAL currently called "CAL 2.0" represent "second-generation" experiments which will aim to be much closer to SOA in terms of metrics such as atom numbers and parameters for atom interferometry. Both experiments, it should be noted, will be well above SOA in terms of microgravity enhanced performance such as temperatures and observation times. Both experiments are trying to pack a lot of science capability into a single general purpose vacuum system, along with a fixed array of supporting hardware.

We discuss here a mission tentatively named the Quantum Explorer, which will be a "third-generation" experiment which will push further towards (and perhaps beyond) the Earth-based SOA, but will also allow for the development of low-cost, customized hardware optimized for a particular experiment, and also readily exchangeable with other hardware modules to enable a multi-user facility. The design and build of this hardware would be a collaboration between PI institutions and NASA scientists and engineers. In addition to this customized hardware, the facility would have a full suite of lasers and electronics similar to a well-equipped Earth-based lab. Astronauts can be engaged as partners to PI teams, allowing the facility to be reconfigured on an hourly time frame, but it will also be capable of purely remote operation. An ultimate goal is to be able to accomplish most Earth based atomic physics experiments in space, with the cost of the additional customized hardware being similar to the costs of a typical Earth-based experiment (where we are admittedly comparing the cost of a few additional pieces of customized flight hardware to the costs of an entire ground experiment).

Lessons learned from CAL

A large number of lessons have been absorbed from the CAL mission, ranging from particulars of different optical and electrical connections to more profound ones on design philosophy and the approach to risk. We mention a few that are particularly guiding our ideas for a follow-on mission.

A more modular design: While CAL was designed to be maintainable and upgradable by astronauts, and has proved remarkably successful in this regard, typical procedures have been exceptionally time-consuming both in planning and execution. A focus on modular design from the beginning, with better human factors engineering, and a minimization and standardization of optical, mechanical and electrical interconnections can dramatically improve this situation. We envision a system in which primary modules can be quickly accessed and replaced with standard procedures, so that modules can be switched out in a few minutes on a daily basis.

Better diagnostics: CAL has been limited by its available diagnostics, which has made trouble shooting time consuming and error-prone. For the Quantum Explorer, we envision a full suite of typical lab equipment such as oscilloscopes and spectrum analyzers which can be dual-purposed to provide both research and diagnostic goals.

A different approach to risk: Traditionally NASA minimizes risk through detailed modelling and analysis in conjunction with a stringent "test as you fly" test program. Obviously this is one's best choice when dealing with missions to Mars or systems that are critical for the safety of human astronauts. For an easily repairable system that does not undergo critical operations, a cheaper approach would be to fly spares for important components, and focus on "ease of repair". Following such an approach can significantly reduce the cost and development time for new modules, freeing up resources for parallel developments that can further mitigate risks.

Top level requirements

	CAL	Quantum Explorer	SOA

Condensed atom number (Rb)	12,000	>5 X10^6 atoms	>1 X10^7 atoms
Atomic Species	Rb87,K39, K41	Rb87,Rb85,K39,K40,K41,TBD	Over 18 atomic species have been Bose condensed to date
Vacuum Lifetime	10 seconds	100 seconds	
Temperatures	< 50 picoKelvin	< 0.5 picoKelvin	30 pK

A number of other capabilities will be available for incorporation into specific PI experiments. These include painted potentials with both blue and red-detuned lasers; Raman and Bragg lasers for atom interferometry. Customized, PI specified, vacuum systems could incorporate optical cavities, quantum engineered surfaces and more.

Science

Most, if not all, of the ultracold atom research developed in topical papers submitted to this decadal survey could potentially be incorporated in this facility. Research enabled by Quantum Explorer could include studying topics as diverse as the nature of the quantum vacuum; quantum chaos and pattern formation; atom lasers and matter-wave holography; matter-wave localization; quantum tunneling and quantum simulations of astrophysical objects, such as the early universe, black holes, and neutron stars as well as condensed matter systems such as high temperature superconductors. We discuss a few of these topics in more detail below. Each would benefit from optimized, PI specified hardware for each individual investigation.

Quantum Droplets: Quantum droplets are a new [6] type of quantum matter consisting of a superfluid mixture stabilized against collapse by quantum fluctuations. These self-trapped superfluid's have been observed on Earth, but only by levitating them which masks their self-bound nature. The planned microgravity experiments will enable a full exploration of their novel properties in microgravity, including their predicted ability to self-cool to near absolute zero. Beyond their intrinsic scientific interest as a new form of liquid matter (which has led to 19 Physical Review Letters and several papers in Science and Nature in the past five years), quantum droplets may provide a novel atomic source for enabling future precision atom interferometer experiments at observation times limited only by the background vacuum (potentially 1000's of seconds).

Advanced atom interferometry with novel quantum states: In most atom interferometers signal scales with the number of atoms observed, while noise increases as the square root of the number of atoms (in the projection noise limit). However, for certain quantum states such as "squeezed states" this atomic shot noise can be suppressed, resulting in large enhancements of sensitivity. It is important that we fully explore and understand such advanced techniques before embarking on costly atom interferometry missions focused on a specific scientific objective.

Atoms in "blue box" potentials: Large box-like traps formed by "painted" blue optical beams allow for the investigation of low density clouds absent of an underlying harmonic potential. Novel space-enabled studies include vortex creation, few-body interactions, beyond mean-field (Lee-Huang-Yang) corrections, and physics on curved manifolds.

Rydberg atom Physics: Space enables novel capabilities including measurement of fundamental constants (Rydberg constant) with circular states and building detectors for single microwave photons, which can be used towards an axion dark matter search.

Quantum-engineered Materials - In microgravity, unconfined atoms can interact with a surface for much longer times and with greater control than is possible on the ground. This allows a number of research directions studying novel surfaces including: quantum reflection of atoms; Bose-Einstein condensates near 2D Materials; Casimir-Polder measurements, exotic low dimensional quantum phases; and studies of third sound and pattern formation in superfluid films.

Shell-shaped condensates are enabled by a microgravity environment as gravity generally prohibits BECs from forming a closed shell. The physics case for these studies is largely based on the intriguing many-body behaviors of shell condensates, from the appearance of new collective modes as the condensate hollows out during a dynamic inflation, to the dynamics of vortices (or vortex lattices) on an ultracold shell.

Platforms

It is uncertain how long beyond 2028 the ISS will be kept operating. However, we are fairly confident that some variety of crewed microgravity laboratory with similar capabilities will be available to researchers. This could be an extended mission ISS, a commercial station such as recently announced by Blue Origins, a NASA follow-on station to ISS, or a series of short duration commercial flights. A follow-on station might not be continuously inhabited, rather hosting periodic visits from astronauts The exact nature of available platforms along with any constraints on power, volume, etc. will, of course, guide the details of the Quantum Explorer design.

We note that costs of building and maintaining a microgravity platform are not included in the costs we discuss below; nor are costs related to transporting hardware to and from a station. One might be expected to share a portion of these costs in the case of commercial platforms.

Costs

The complexity of the Quantum Explorer instrument will be similar to CAL's and hence we expect the cost to be similar. Cost saving's based on the reuse of CAL or BECCAL designs will be balanced by the need for improved performance. We note that producing a system that is easier to maintain and upgrade allows for a range of initial price points to match NASA's needs. We can envision beginning with a simplified system (albeit one that offers meaningful improvements over previous missions), and then upgrading it further over time. The modular nature of the instrument will make it ideal for partnerships, both with non-Nasa U.S agencies, PI institutions, and international organizations. In particular it allows for meaningful partnerships that are largely independent, allowing significant schedule agility. For example if customized vacuum systems are being built simultaneously at several institutions, delays at one institution might only minimally effect the project as a whole.

Based on experience with CAL, we might expect an over-all cost in the vicinity of 100M in 2024 dollars for an initial "no-frills" build, while the costs of customized hardware built at JPL might start in the vicinity of $2-$3 million. A possible breakout of cost by year is shown in table 1, showing different price points for instruments with different complexity.

The cost information discussed here is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

CAL NASA Cost File Data		**Phase A**	**Phase B**	**Phase C/D**	**Phase E**	**Total**
		FY13	FY14	FY15-18	FY19-21	
		8 months	14 months	48 months	36 months	
each phase in $M		2.4	11.3	51.6	15.0	80.3
Inflate 2.5% to FY24 Phase A		3.1	14.9	67.7	19.7	105.4
Normalize Schedule		12 months	12 months	36 months	36 months	
Normalize cost to schedule		**4.7**	**12.7**	**67.7**	**19.7**	**104.8**
Complexion factor	1	4.7	12.7	67.7	19.7	104.8
	1.1	5.2	14.0	74.5	21.6	115.3
	1.2	5.6	15.3	81.3	23.6	125.8
	1.3	6.1	16.6	88.0	25.6	136.3

Table 1. CAL cost data, inflated to reflect a possible FY24 start for Quantum. Explorer. We expect QE to be roughly in line with these numbers. "Complexion factor" reflects increased costs arising from incorporating more features into the initial build.

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